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Test of APEX for Nine Forested Watersheds in East Texas

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ABSTRACT

Hydrologic/water quality models are increasingly used to explore management and policy alternatives for managing water quality and quantity from intensive silvicultural practices with best management practices (BMPs) in forested watersheds due to the limited number of and cost of conducting watershed monitoring. The Agricultural Policy/Environmental eXtender (APEX) model was field-tested using 6 yr of data for flow, sediment, nutrient, and herbicide losses collected from nine small (2.58 to 2.74 ha) forested watersheds located in southwest Cherokee County in East Texas. Simulated annual average stream flow for each of the nine watersheds was within ± 7% of the corresponding observed values; simulated annual average sediment losses were within ± 8% of measured values for eight out of nine watersheds. Nash-Sutcliffe efficiency (EF) values ranged from 0.68 to 0.94 based on annual stream flow comparison and from 0.60 to 0.99 based on annual sediment comparison. Similar to what was observed, simulated flow, sediment, organic N, and P were significantly increased on clear-cut watersheds compared with the control watersheds. APEX reasonably simulated herbicide losses, with an EF of 0.73 and R^2 of 0.74 for imazapyr, and EF of 0.65 and R^2 of 0.68 for hexazinone based on annual values. Overall, the results show that APEX was able to predict the effects of silvicultural practices with BMPs on water quantity and quality and that the model is a useful tool for simulating a variety of responses to forest conditions.

The availability of clean, contaminant-free water is increasingly crucial with ever increasing demands on finite resources. Forested watersheds are generally associated with higher water quality than watersheds with other major land uses (USEPA, 1995). However, the amount of sediment and nutrients leaving forested watersheds may be subject to short-term increases due to certain silvicultural practices such as timber harvesting, mechanical treatments, and fertilization (Moore and Norris, 1974; Yoho, 1980; Binkley et al., 1999; McBroom et al., 2001; Ice et al., 2003). Silvicultural practices have been changed over the last 20 to 30 yr. Contemporary silvicultural practices increasingly involve the use of herbicides for site preparation and weed control, fertilization, and soil amelioration methods such as bedding and tillage. Moreover, best management practices (BMPs) now include streamside management zones (SMZs) on intermittent streams (Texas Forestry Association, 2000). However, field studies conducted specifically to examine effects of these combinations of mechanical and chemical treatments with the implementation of contemporary BMPs on water quality are limited. The considerable expense and collection difficulties in forestry studies caused by the time duration, natural rainfall variation, substantial land area requirements, field personnel, and automated sampling equipment requirements often make field studies unfeasible. Therefore, hydrologic/water quality computer models tested with measured data can provide a much more efficient and effective way to evaluate the effects of silvicultural practices on water quality than what is feasible through monitoring by itself in forestry studies.

The Agricultural Policy/Environmental eXtender (APEX) model (Williams et al., 2000) was developed to evaluate various land management strategies including sustainability, erosion (water and wind), water supply and quality, soil quality, plant competition, weather, and pests. APEX has been modified to enhance factors associated with forestry conditions such as rainfall interception by canopy, litter, subsurface flow, nutrient movement, and routing enrichment ratios as reported in Saleh et al. (2004). Historical data (1980–1985) of measured flow, sediment losses, and nutrient (NO_3–N, organic N, PO_4–P, organic P) losses from nine small watersheds in East Texas, with three watersheds for each of the three treatments (without BMPs): (a) control (CON); (b) clear-cut followed by shearing, windrowing, and burning (SHR); and (c) clear-cut followed by roller chopping and burning (CHP) were used to test APEX. Saleh et al. (2004) concluded that the modified APEX was able to reasonably simulate water quality and quantity from a variety of forest conditions including mature forest, harvested, site prepared, replanted, and forest regrowth scenarios. The flexibility of APEX has led to its adoption within the Conservation Effects Assessment Project (CEAP) for national assessment. The purpose of the national assessment is to estimate the benefits obtained from USDA conservation programs at the national level. At the CEAP survey sample points, there were no measured responses of runoff, sediment, and/or nutrient loss to calibrate the model. Model parameterization has to be based on previous experience or studies near the sample points with closely matched field characteristics, management, and observed weather. As part of the CEAP modeling effort, the objective of this study was to test the APEX model using flow, sediment, nutrient, and herbicide losses collected from 1999 to 2004 for the same

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Abbreviations: APEX, Agricultural Policy/Environmental eXtender; EPIC, Environmental Policy Impact Calculator; BMPs, best management practices; SMZ, streamside management zones; PE, percent error; EF, model efficiency or Nash-Sutcliffe efficiency.

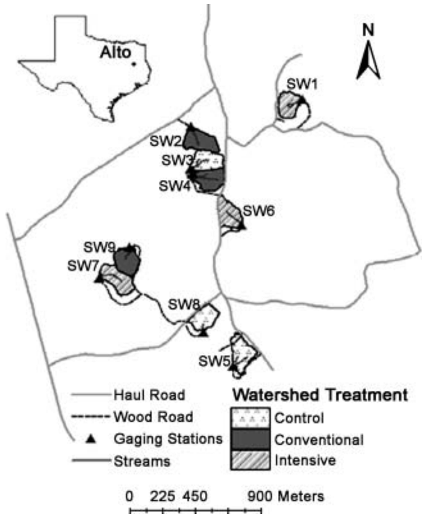

Fig. 1. The location of the Alto watersheds used in the study.

nine watersheds as in Saleh et al. (2004), with three watersheds for each of the following treatments: (a) undisturbed control; (b) clear-cut followed by herbicide site preparation, replanting, and herbicide herbaceous release (conventional); and (c) clear-cut followed by herbicide site preparation, subsoil, fertilizer application, replanting, and herbicide herbaceous release (intensive).

MATERIALS AND METHODS

Watershed and Treatment Description

The nine forested watersheds (2.58–2.74 ha) selected for this study are located in southwest Cherokee County in the Neches River Watershed in East Texas (31°36′07″ N, 95°14′12″ W), denoted as watersheds SW1 to SW9 (Fig. 1). The site was characterized by a humid subtropical climate with mean annual precipitation of 1170 mm and mean annual temperature of 19°C (Chang et al., 1996). Dominant soils include the Cuthbert and Kirvin series (clayey, mixed, thermic Typic Hapludults) typically on upland ridges and the Rentzel series (loamy siliceous, thermic Arenic Plinthaquic Paleudult) typically along stream courses. The watersheds were originally instrumented in 1980 to evaluate the effects of clear-cut harvesting and mechanical site preparation on storm flow and water quality (Blackburn et al., 1986; Saleh et al., 2004). Watershed monitoring was resumed in January 1999. This study employed a paired watershed approach to evaluate the effects of silvicultural activities on water quantity and quality, with 3 yr of pretreatment (1999–2001). The nine watersheds were blocked by hydrogeomorphic factors. In this 3 by 3 design, one watershed from each of the three blocks served as a control, while the other two were clear-cut and regenerated using either conventional or intensive site preparation methods with BMPs (Fig. 1, Table 1). Clear-cut, aerial broadcast herbicide site preparation, planting with loblolly pine (*Pinus taeda* L.), and aerial broadcast herbicide herbaceous release were conducted on the conventional and intensive watersheds. The intensive watersheds were also subsoiled and fertilized with an additional banded release herbicide application in the second year after stand establishment (Table 1). SMZs consistent with Texas BMPs were left along all stream channels and were mechanically thinned at time of clear-cut harvest according to Texas BMPs. Watersheds are predominantly covered by loblolly pine plantation (Table 2).

Table 2. Pretreatment stand and stock table for overstory and midstory vegetation.

Watershed	Pine		Hardwood		Midstory	
	Upland	SMZ†	Upland	SMZ	Upland	SMZ
	stems ha^{-1}					
SW1	683.6	370.6	436.5	642.5	4365.5	3459.4
SW2	341.8	90.6	24.7	65.9	4159.4	4077.1
SW3	712.5	86.5	284.2	374.8	2882.9	741.3
SW4	12.4	32.9	0	24.7	2100.3	3212.3
SW5	205.9	197.7	626	877.2	2223.9	1111.9
SW6	1375.5	1997.4	399.5	308.9	1853.2	5806.8
SW7	836	667.2	531.3	568.3	2799.6	3459.4
SW8	1198.4	111.2	41.2	321.2	4200.6	2594.5
SW9	869	506.5	679.5	914.3	2141.5	1482.6

† SMZ, streamside management zones.

Monitoring Data

Precipitation was measured with a system consisting of a Qualimetrics 6011-A tipping-bucket rain gauge, ISCO Model 674 tipping-bucket recording rain gauges, and Nova Linx Model 260–2510 National Weather Service standard

Table 1. Silvicultural treatment activities for the study watersheds.†

Treatment	Group ID	Watershed (year established)	Treatment activity	Date
Control	1	SW3 and SW5 (1982), SW8 (1989)	–	–
Conventional	2	SW2 (1982), SW4 (1997), SW9 (1982)	Clear-cut harvest	April–June 2002
			Aerial broadcast herbicide site preparation of Arsenal (1.17 L ha^{-1} imazapyr) and Accord (4.68 L ha^{-1} glyphosate)	28–29 Sept. 2002
			Machine planting of loblolly pine	11–17 Dec. 2002
			Hand inter-planting of loblolly pine	3–6 Mar. 2003
			Aerial broadcast herbaceous weed control of Oustar (0.81 L ha^{-1})	3–7 Apr. 2003
Intensive	3	SW1(1982), 6 (1989), 7 (1982)	Clear-cut harvest	April–June 2002
			Aerial broadcast herbicide of Arsenal (1.17 L ha^{-1}) Accord (4.68 L ha^{-1})	28–29 Sept. 2002
			Subsoil (0.6 m deep) on the contour	14–24 Oct. 2002
			Fertilizer application (aerial broadcast) of di-ammonium phosphate (280.2 kg ha^{-1})	15–17 Dec. 2002
			Hand planting of loblolly pine	17–19 Dec. 2002
			Herbaceous weed control of Oustar (0.81 L ha^{-1})	3–7 Apr. 2003
			Hand-applied banded herbaceous weed control of Oustar (0.40 L ha^{-1})	1–2 Apr. 2004

† Arsenal is a registered trade name held by BASF Corporation; Accord and Oust are registered trade names held by DuPont Corporation. The use of trade and corporation names does not constitute an endorsement by the authors or their respective employers.

Table 3. Selected methods and related parameters for this study.

Component	Method	Related parameter
Potential evapotranspiration	Hargreaves method (Hargreaves and Samani, 1985) (modified)	Hargreaves PET equation exponent = 0.6
Runoff volume	NRCS curve number method (Mockus, 1969) (modified)	SCS curve number index coefficient = 0.4
Peak flow	Modified rational method	Peak rate–rainfall energy adjustment factor = 0.4
Erosion	MUST (a variation of MUSLE) (Williams, 1995)	General parameters for RUSLE, but the rainfall energy factor replaced by runoff volume in mm and the peak runoff rate in mm h^{-1} calculated within the model
Pesticide	GLEAMS (Leonard et al., 1987) enrichment ratio (modified)	N enrichment ratio coefficient for routing = 0.3 N enrichment ratio exponent for routing = 0.1 P enrichment ratio coefficient for routing = 0.05 P enrichment ratio exponent for routing = 0.1

nonrecording rain gauges. These gauges were distributed such that each watershed has at least one rain gauge, with the recording instruments connected to Campbell Scientific CR500/CR510 data loggers or Onset Hobo Event loggers. Precipitation amounts were measured to the nearest 0.254 mm for every event.

Stream flow was monitored at the outlet (Fig. 1) of each watershed with 0.91 m H-flumes. Watershed runoff first flows into a sediment trap, then an approach section of 4.3 m long by 1.2 m wide by 0.9 m high before passing through the 0.91 m H-flume. An Intermountain Environmental potentiometric float and pulley level recorder installed in the stilling well at the sidewall of the flume measured stage. Discharge was calculated from stage recordings stored in 5-min intervals in the data logger.

Water samples were collected using Coshocton wheel samplers and ISCO 3700 pumping samplers. Coshocton wheel samplers were installed in this study to provide a statistical justification for comparing sediment load measurement differences between Coshocton wheels and ISCO samplers. Two simultaneously sampling ISCO samplers were installed at each watershed, with one containing a buffer solution for herbicide analysis and the other without buffer. The initiation level to trigger the ISCO sampler to take sample during a storm runoff event was set to 3.04 cm. Samples were automatically collected at 30-min intervals until stage fell below the initiation level.

Water samples were collected as soon as possible following storm runoff events. Samples were iced and transported to the laboratory for compositing and preservation. Stage data were processed and hydrographs were generated for each watershed. Sample collection times on the hydrographs were determined. For most runoff events, samples were composited based on hydrograph phase, with one set representing the rising limb, one set the peak, and one the recession limb. Additional composites were generated for larger storm events and for complex hydrographs with multiple peaks. Individual samples were sent when few samples were collected or during more extreme runoff events.

Individual samples were equal volume weighted and composited together. An aliquot of the composited samples was drawn off for chemical analysis. Aliquots were poured into a 1-L unpreserved bottle for analysis of total suspended solids (TSS), total dissolved solids (TDS), nitrate-nitrogen (NO_3^-), nitrate-nitrite nitrogen (NO_3–NO_2), and phosphate (PO_4^{-3}). Aliquots were poured into 500-mL bottles and preserved with sulfuric acid for analysis of total phosphorus (TP), ammonia nitrogen (NH_4^+), and total Kjeldahl nitrogen (TKN). Samples were then packed on ice and delivered to Ana-Lab in Kilgore, TX. Analysis methods conformed to established APHA and EPA methodology, with method EPA 300.0 used for analysis of NO_3 and NO_3–NO_2, EPA 350.1 for NH_4, EPA 351.2 for TKN, EPA 160.2 for TSS, EPA 160.1 for TDS, EPA 365.3 for PO_4, and EPA365.4 for TP (APHA, 2005; USEPA, 2003).

Herbicide samples were collected before treatment (to check if there were background sources of these herbicides) and following applications using one of the two ISCO units installed at each gauging station. Samples were composited by volume and used to run a preliminary screening analysis to determine if herbicide concentrations exceed the method detection limit of 1.0 ppb. Up to five discrete samples, 150 mL each, were composited to represent the rising and peak phases of the hydrograph. Samples representing the rising phase included the peak and the four discrete samples immediately preceding the peak. Samples representing the falling phase included the five discrete samples immediately following the peak. Besides the composite samples, 50 mL from each discrete parent sample collected was preserved by freezing and was analyzed for herbicides in the event that the screening procedure of the composite samples returned a concentration greater than 1.0 ppb.

Simulation Methodology

The APEX model (Williams et al., 2000) was developed as an extension of the Environmental Policy Impact Calculator (EPIC) model (Williams, 1989; Williams and Sharpley, 1989) for use in whole farm and small watershed management. It is

Table 4. Characteristics of watersheds.

	Control			Conventional			Intensive		
Parameter	SW3	SW5	SW8	SW2	SW4	SW9	SW1	SW6	SW7
Upland									
Area (ha)	2.02	2.36	2.18	2.29	2.3	2.39	2.34	2.36	2.38
Average upland slope (m m^{-1})	0.15	0.15	0.13	0.13	0.15	0.135	0.12	0.12	0.13
Channel length (km)	0.180	0.167	0.079	0.170	0.090	0.120	0.100	0.110	0.078
Floodplain									
Area (ha)	0.62	0.35	0.44	0.28	0.36	0.34	0.27	0.3	0.36
Channel slope (m m^{-1})	0.14	0.08	0.10	0.10	0.12	0.10	0.11	0.089	0.09
Channel length (km)	0.310	0.176	0.220	0.140	0.180	0.172	0.135	0.150	0.179
Total area (ha)	2.64	2.71	2.62	2.57	2.66	2.73	2.61	2.66	2.74

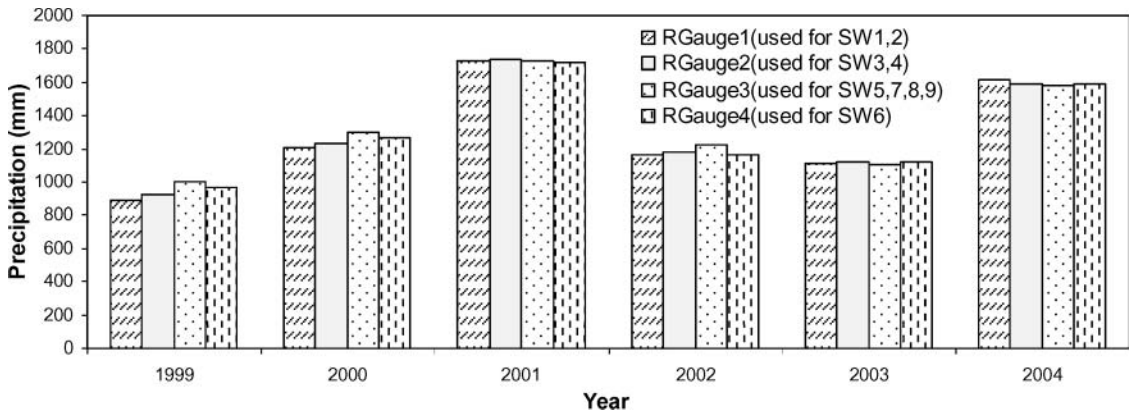

Fig. 2. Annual total precipitation of each watershed.

based on state-of-the-art technology taken from several mature and well tested models.

The individual field simulation is performed using EPIC functions. EPIC can simulate hydrology, erosion, nutrient, soil quality, plant growth/competition, weather, pests, and economics. It operates on a continuous basis using a daily weather data, soil characteristics, land use management practices such as tillage, planting, harvesting, and nutrient and pesticide applications. This model offers options for simulating potential evapotranspiration, water erosion/sediment, surface runoff, peak runoff rate, etc. Detailed description and discussions of EPIC were given by Williams (1990, 1995). Selected methods and related model parameters are listed in Table 3.

In addition to the EPIC functions, APEX has components for routing water, sediment, nutrients, and pesticides across landscapes and channels to watershed outlets (Williams et al., 2000). A more detailed description of APEX was given by Williams and Izaurralde (2006). The model has been enhanced and tested in a similar water quality study (1980–1985) on the same nine watersheds by Saleh et al. (2004). The enhancement for forestry included the development of new parameters to estimate routing enrichment ratios for N and P. These values for the study watersheds are listed in Table 3. Other model parameters were defaults in the APEX parameter database, including parameters for crops, fertilizers, tillage operations, and pesticides.

Each of the nine watersheds was subdivided into two subareas: upland and floodplain. Upland treatment activities are summarized in Table 1. An SMZ was left in the floodplain area along all stream channels for all treatments. The characteristics of the two subareas for each watershed are listed in Table 4. Cuthbert soils are dominant in upland areas, while Rentzel soils are more prevalent along SMZs. Soil property data, including layer depth, bulk density, wilting point, field capacity, percentage sand, percentage silt, pH, and percentage organic carbon, were retrieved from the Soil Survey Geographic (SSURGO) database. The daily on-site precipitation measured from four rain gauges among the nine watersheds for the 6-yr simulation period was used. The total annual precipitation from each rain gauge is plotted in Fig. 2. Rainfall was not found to be significantly different among watersheds for each year. Therefore, potentially different responses in stream flow could be considered treatment effects as opposed to variation in precipitation among watersheds. Daily maximum and minimum temperature, daily total solar radiation, average relative humidity, and average wind velocity were generated using long-term monthly weather statistics in the APEX weather generator parameter database for Lufkin, TX.

Evaluation of Model Performance

Several statistics were used to evaluate APEX performance in estimating flow, sediment, nutrient, and herbicide losses for the nine forested watersheds. Simulated and observed values were compared using mean, standard deviation, R^2, percent error (PE), and Nash-Sutcliffe efficiency (EF) (Nash and Sutcliffe, 1970). APEX performance was also evaluated by conducting statistical tests with SAS (SAS Institute, 1999). Data transformations were performed based on work by Box

Table 5. Observed and simulated stream runoff based on the annual values of 1999–2004 (N = 6).†

Treatment	Watershed	Observed Mean	Observed Std	Simulated Mean	Simulated Std	PE	EF	R^2	p Value‡
		mm yr^{-1}				%			
Control	SW3	29.65	28.33	31.52	21.10	6.3	0.85	0.90	0.69
	SW5	34.68	35.80	32.75	34.82	−5.6	0.88	0.88	0.72
	SW8	23.24	30.14	24.61	27.53	5.9	0.68	0.69	0.85
	Average	29.19	30.59	29.62	27.67	1.5	0.86	0.86	0.93
Conventional	SW2	90.18	52.96	86.92	65.65	−3.6	0.88	0.95	0.68
	SW4	35.52	23.26	37.45	23.27	5.4	0.92	0.93	0.50
	SW9	72.72	57.88	73.55	47.03	1.1	0.94	0.97	0.90
	Average	66.14	38.88	65.96	39.85	−0.3	0.97	0.97	0.96
Intensive	SW1	72.73	53.93	69.68	55.36	−4.2	0.94	0.95	0.58
	SW6	99.34	64.07	100.47	70.64	1.1	0.85	0.88	0.92
	SW7	54.67	33.18	55.62	37.35	1.7	0.74	0.79	0.89
	Average	75.58	47.78	75.26	52.19	−0.4	0.89	0.91	0.96

† PE, percent error; EF, Nash-Sutcliffe efficiency.
‡ H_0: the difference between the simulated and observed annual flow was not significantly different from zero; H_0 is rejected if p value is less than the level of significance ($\alpha/2$ = 0.025).

Table 6. Observed and simulated stream flow based on the monthly values of 1999–2004 ($N = 72$).†

	Control			Conventional			Intensive		
Parameter	SW3	SW5	SW8	SW2	SW4	SW9	SW1	SW6	SW7
Observed mean	2.47	2.89	1.94	7.52	2.96	6.06	6.06	8.28	4.56
Simulated mean	2.63	2.73	2.05	7.24	3.12	6.13	5.81	8.37	4.64
Observed std	7.89	10.23	8.81	18.32	9.15	16.46	16.32	19.26	11.44
Simulated std	3.94	7.36	5.82	16.13	6.70	13.41	12.53	20.05	10.44
EF	0.65	0.80	0.67	0.71	0.86	0.84	0.81	0.44	0.81
R^2	0.80	0.84	0.70	0.71	0.91	0.86	0.84	0.54	0.81
p Value‡	0.78	0.76	0.85	0.82	0.69	0.93	0.76	0.95	0.89

† EF, Nash-Sutcliffe efficiency.
‡ H_0: the difference between the simulated and observed monthly flow was not significantly different from zero; H_0 is rejected if p value is less than the level of significance ($\alpha/2 = 0.025$).

and Cox (1964) to stabilize variances before conducting statistical tests. Paired t tests were performed to assess if the difference between simulated and observed values was significantly different from zero. The ANOVA contrast analysis was performed to assess whether there were statistically significant differences on observed flow, sediment, and nutrient losses from treatment-grouped watersheds. The test results were compared with the results from the same test conducted based on simulated values to determine if the model detects the differences, if any.

RESULTS AND DISCUSSION

Stream Flow

Summary statistics for observed and simulated stream flow are compared by watershed in Table 5. The simulated average flow for each watershed is within ± 7% of the corresponding observed value. The PE values for all the treatments are within ± 2% based on the average values for each treatment. The simulated flow standard deviation values are in good agreement with observed values for all watersheds, indicating the similarity in flow probability distributions. The EF values ranged from 0.68 to 0.94. The R^2 values ranged from 0.69 to 0.97. Explicit standards for model evaluation were not established (Chung et al., 1999). However, Chung et al. (1999) used the criteria of EF > 0.3 and $R^2 > 0.5$ to assess if the model results were satisfactory for EPIC annual output comparison. Ramanarayanan et al. (1997) suggests that model prediction was acceptable if EF > 0.4 and $R^2 > 0.5$. In Adeuya et al. (2005), the criteria of EF > 0.45 and $R^2 > 0.50$ were selected as the evaluation criteria for GLEAMS-NAPRA calibration and validation. Loague and Green (1991) stated that a

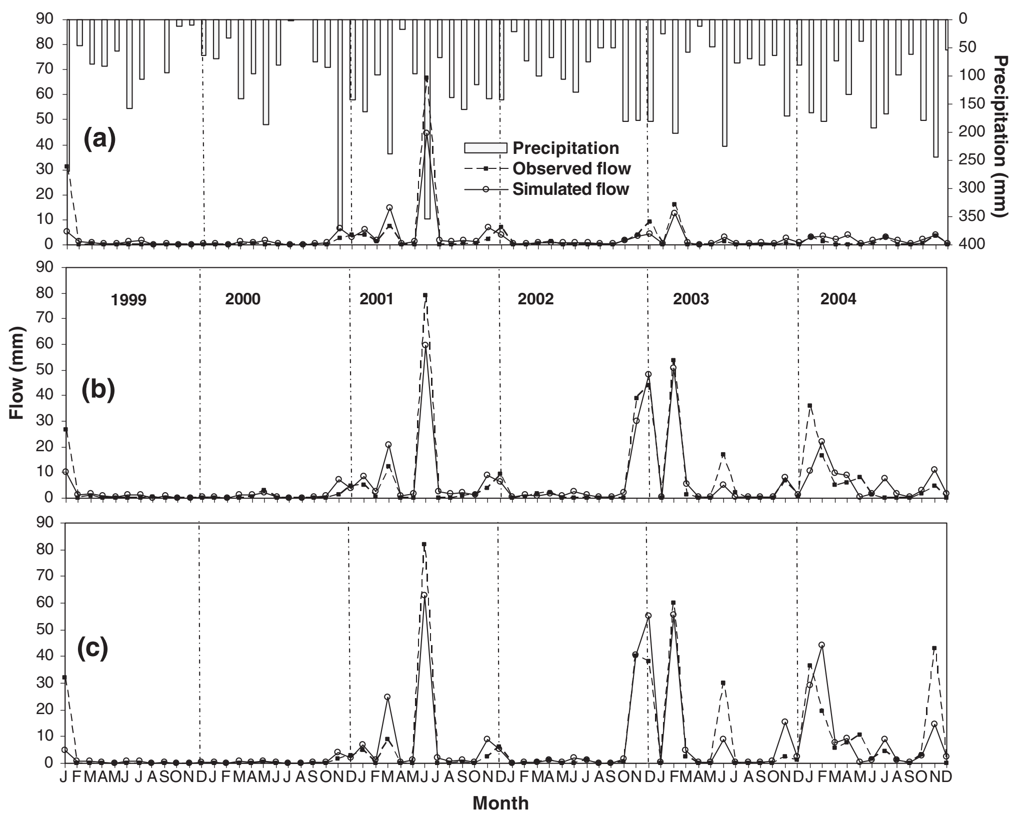

Fig. 3. Simulated and measured average monthly flow (average of three watersheds) for (a) control, (b) conventional, and (c) intensive treatments.

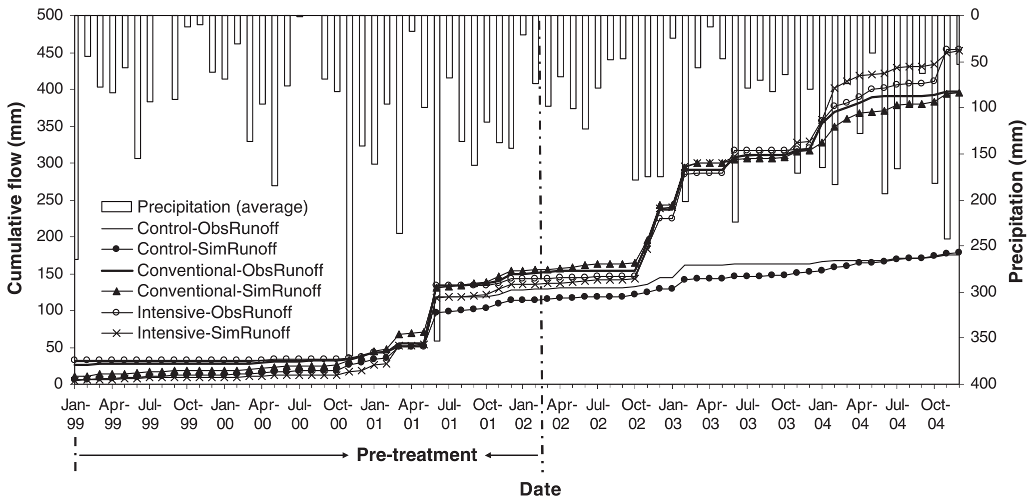

Fig. 4. Simulated and measured average cumulative flow for the three treatments and precipitation.

model's performance was judged acceptable if it is not possible to reject the hypothesis in test statistic of no difference between observed and predicted values. In this regard, APEX reasonably tracked the monthly observed flow for all watersheds with EF > 0.4, and $R^2 >$ 0.5 (Table 6). The p values of the paired t tests are all greater than 0.05, indicating that the difference between the simulated and observed annual flow is not significantly different from zero (Tables 5 and 6).

Monthly time series of observed and simulated flow for each treatment (average of three watersheds) are plotted in Fig. 3, which shows the similarity of measured and simulated flow trends. In general, APEX underpredicted flow that occurred in June 2003 for clear-cut watersheds. Figure 4 shows the cumulative flow for the three treatments. Similar to field observations, APEX simulated very low flow for the pretreatment period 1999 through 2000 (Fig. 3) when the precipitation was low. Most precipitation was retained by vegetation and soils. Highest flow was observed and simulated in June 2001 when the tropical storm Allison occurred, which produced almost 300 mm of rain in a 3-d period. Before treatment in April 2002, the intensive watersheds produced 143 mm (average of three replicates) of measured flow from January 1999 to March 2002; APEX simulated an average of 136 mm flow from those watersheds for the same period. The conventional watersheds produced 152 mm flow on average as compared with the simulated 156 mm for this period. The observed and simulated average flow for the control watersheds was 129 and 115 mm, respectively, for the period. Similar to what was observed, the simulated flow as a percentage of precipitation for this period was about 3% for all treatments.

For the pretreatment period, there were no statistically significant differences among flow from grouped watersheds for both observed and simulated values

Table 7. Statistical tests for hypothesis H_0: no significant difference on flow, sediment, and nutrient losses from treatment-grouped watersheds.†

		p Value			
		Pretreatment		Post-treatment	
Parameter	Contrast treatment group	Observation	Simulation	Observation	Simulation
Flow	1 vs. 2	0.941	0.310	*0.028*	*0.015*
	1 vs. 3	0.893	0.619	*0.016*	*0.005*
	2 vs. 3	0.951	0.578	0.654	0.400
Sediment	1 vs. 2	0.626	0.663	0.075	0.074
	1 vs. 3	0.566	0.668	*0.048*	*0.043*
	2 vs. 3	0.929	0.994	0.943	0.704
Organic N	1 vs. 2	0.693	0.835	*0.059*	*0.100*
	1 vs. 3	0.325	0.556	*0.023*	*0.024*
	2 vs. 3	0.535	0.433	0.616	0.323
Mineral N	1 vs. 2	0.767	0.483	0.243	0.226
	1 vs. 3	0.346	0.485	*0.017*	0.177
	2 vs. 3	0.503	0.186	0.098	0.862
Organic P	1 vs. 2	0.552	0.749	*0.040*	0.090
	1 vs. 3	0.946	0.305	*0.040*	*0.020*
	2 vs. 3	0.596	0.461	0.820	0.310
Soluble P	1 vs. 2	0.267	0.466	0.109	0.083
	1 vs. 3	0.990	0.501	*0.027*	*0.015*
	2 vs. 3	0.266	0.953	0.051	0.237

† Italicized p values indicate that there were statistically significant differences on testing values from treatment-grouped watersheds at the 90% significant level.

Table 8. Observed and simulated sediment loss based on the annual values of 1999–2004 (N = 6).†

Treatment	Watershed	Observed Mean	Observed Std	Simulated Mean	Simulated Std	PE	EF	R^2	p Value‡
		kg ha^{-1}				%			
Control	SW3	90.03	148.25	85.17	165.06	−5.4	0.92	0.94	0.79
	SW5	5.70	11.04	6.83	15.29	19.8	0.86	0.99	0.58
	SW8	16.76	36.82	17.67	42.30	5.4	0.97	0.99	0.73
	Average	37.50	64.77	36.56	74.19	−2.5	0.94	0.97	0.88
Conventional	SW2	120.62	121.76	122.00	126.71	1.1	0.99	0.99	0.91
	SW4	41.17	72.51	38.67	85.98	−6.1	0.95	0.99	0.72
	SW9	41.00	35.89	38.00	32.56	−7.3	0.83	0.84	0.62
	Average	67.60	70.00	66.22	74.07	−2.0	0.99	0.99	0.65
Intensive	SW1	103.12	191.09	109.17	136.76	5.9	0.68	0.70	0.91
	SW6	186.26	178.24	195.83	160.13	5.1	0.85	0.85	0.76
	SW7	22.14	19.01	22.17	21.19	0.1	0.60	0.68	0.99
	Average	103.84	111.79	109.06	97.54	5.0	0.82	0.82	0.81

† PE, percent error; EF, Nash-Sutcliffe efficiency.
‡ H_0: the difference between the simulated and observed annual sediment loss was not significantly different from zero; H_0 is rejected if p value is less than the level of significance ($\alpha/2 = 0.025$).

(Table 7). However, the p values indicate that both observed and simulated flow from the conventional and intensive watersheds was greater than that from the control watersheds for the post-treatment phase (Table 7). After treatment, storm flow increased on clear-cut watersheds mainly due to the reduction in evapotranspiration. From April to December 2002, on average, conventional and intensive watersheds produced 85 and 81 mm of measured flow, respectively, as compared with 16 mm from the control watersheds. APEX simulated 87, 102, and 14 mm flow for the same period of time for the conventional, intensive, and control watersheds, respectively. Observed flow as a percentage of precipitation for this period averaged about 1, 8, and 8% for the control, conventional, and intensive watersheds, respectively, as compared with the corresponding percentage of simulated flow vs. precipitation of about 1, 8, and 9%. During 2003 and 2004, conventional and intensive watersheds continued to produce more storm flow than control watersheds (Fig. 3). Overall, average annual evapotranspiration was higher from control watersheds. Both observed and simulated flow as a percentage of precipitation for this period averaged about 2% for the control, 9% for the conventional, and 11% for the intensive watersheds.

Sediment

The model performance for sediment loss was acceptable with EF values ranging from 0.60 to 0.99 and R^2 values ranging from 0.68 to 0.99 for the nine watersheds based on annual values (Table 8). The EF values were larger than 0.4 and R^2 values larger than 0.5 except for SW6 and SW9 based on monthly comparisons (Table 9). The simulated standard deviations are in close agreement with observed values for all watersheds (Tables 8 and 9), indicating the similarity in sediment loss probability distributions. The p values of paired t tests indicate that the differences between the simulated and observed sediment losses are not significantly different from zero for all the watersheds (Tables 8 and 9).

Monthly time series of observed and simulated sediment losses for each treatment (average of three watersheds) are plotted in Fig. 5. APEX underpredicted sediment loss in June 2003, which was associated with the flow underpredictions in June 2003. Figure 6 shows the cumulative sediment losses for the three treatments. Similar to what were observed, simulated sediment losses during 1999 and 2000 were very low corresponding to very low flow. Highest sediment losses were observed and simulated in June 2001, resulting from Tropical Storm Allison. Forested headwater streams have a high potential for natural, geologic erosion which can be greater than effects from silvicultural activities (McBroom et al., 2003). After treatment, sediment losses were greater from intensive watersheds than from control watersheds as indicated by the p value in Table 7. Increased stream flow resulting from reduced evapotranspiration and greater soil surface disturbance (subsoiling) increased sediment loss potential.

Table 9. Observed and simulated sediment loss based on the monthly values of 1999–2004 (N = 72).†

Parameter	Control SW3	Control SW5	Control SW8	Conventional SW2	Conventional SW4	Conventional SW9	Intensive SW1	Intensive SW6	Intensive SW7
Observed mean, kg ha^{-1}	7.50	0.48	1.40	10.05	3.43	3.42	8.59	15.52	1.85
Simulated mean, kg ha^{-1}	7.08	0.53	1.47	10.17	3.22	3.15	9.08	16.33	1.86
Observed std, kg ha^{-1}	45.68	3.16	10.71	37.69	21.69	11.24	56.75	57.13	6.51
Simulated std, kg ha^{-1}	37.44	4.01	12.26	41.72	24.99	12.02	37.07	55.84	6.63
EF	0.85	0.91	0.97	0.43	0.97	0.10	0.80	0.32	0.75
R^2	0.87	0.99	0.99	0.56	0.99	0.34	0.88	0.43	0.77
p Value‡	0.84	0.64	0.72	0.97	0.66	0.83	0.87	0.88	0.96

† EF, Nash-Sutcliffe efficiency.
‡ H_0: the difference between the simulated and observed monthly sediment loss was not significantly different from zero; H_0 is rejected if p value is less than the level of significance ($\alpha/2 = 0.025$).

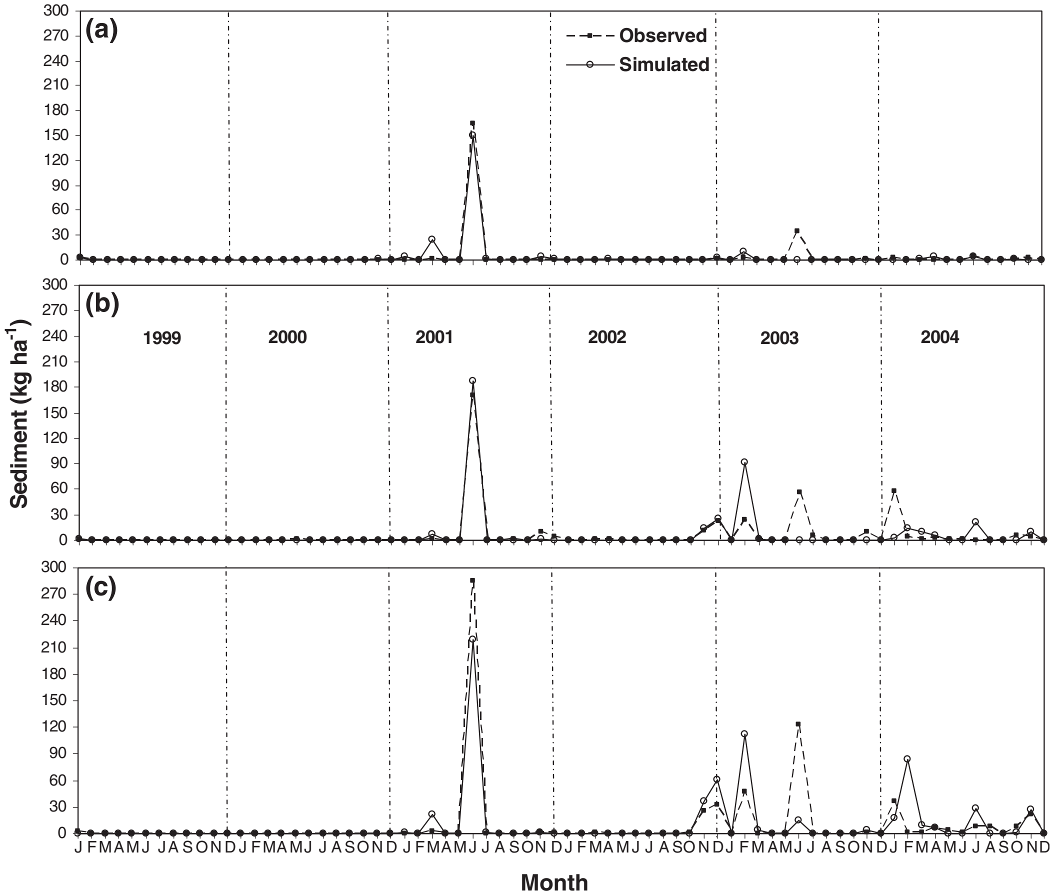

Fig. 5. Simulated and measured average monthly sediment (average of three watersheds) for (a) control, (b) conventional, and (c) intensive treatments.

Nutrient Losses

Nutrient losses were relatively low for these forested watersheds. As indicated in Saleh et al. (2004), due to very low loads of nutrient observed, any small error in magnitude can result in a large percentage error, ultimately leading to lower model efficiencies; therefore, the PE and EF were not used. The means and standard deviations of the observed and simulated nutrient losses for the nine watersheds generally compare closely, indicating the similarity in nutrient loss probability distributions. The differences between observed and simulated annual values were not significantly different from zero except for organic N loss from SW4, and mineral N losses from SW3 and SW4 (Table 10). The p values based on monthly comparisons indicate that most of the differences (in 30 out of 36 compari-

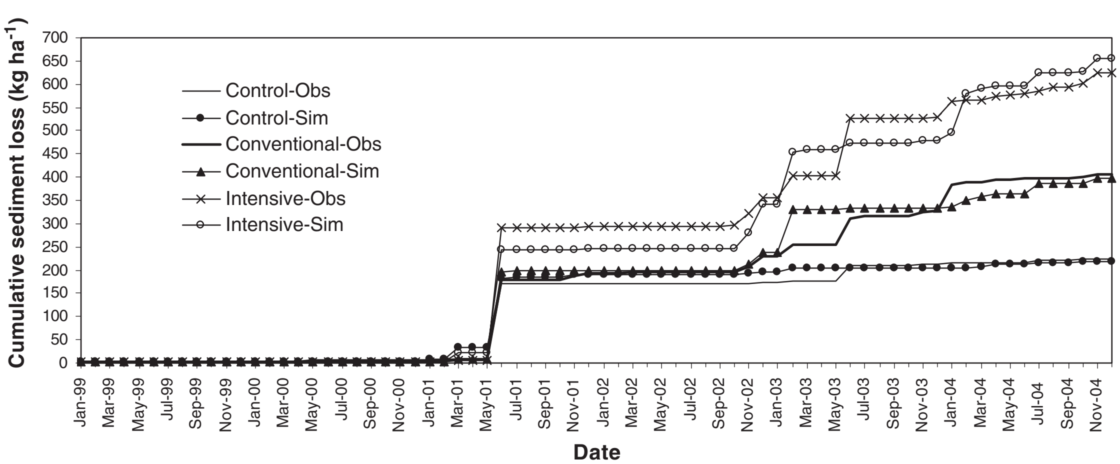

Fig. 6. Simulated and measured average cumulative sediment loss for the three treatments.

Table 10. Observed and simulated nutrient losses statistics based on annual values for each watershed ($N = 6$).

Parameter	Control SW3	Control SW5	Control SW8	Control Avg.	Conventional SW2	Conventional SW4	Conventional SW9	Conventional Avg.	Intensive SW1	Intensive SW6	Intensive SW7	Intensive Avg.
	kg ha^{-1}											
Organic N												
Observed mean	0.244	0.086	0.075	0.135	0.569	0.144	0.570	0.428	0.879	0.806	0.317	0.667
Simulated mean	0.241	0.085	0.134	0.153	0.842	0.035	0.478	0.455	0.846	1.572	0.219	0.880
Observed std	0.280	0.049	0.114	0.131	0.382	0.078	0.515	0.308	0.901	0.668	0.251	0.501
Simulated std	0.449	0.188	0.314	0.317	1.341	0.045	0.591	0.524	1.200	1.250	0.194	0.800
R^2	0.92	0.01	0.89	0.92	0.08	0.28	0.58	0.16	0.81	0.64	0.42	0.84
p Value†	0.97	0.99	0.52	0.83	0.62	*0.01*	0.58	0.91	0.89	0.07	0.27	0.25
Mineral N												
Observed mean	0.067	0.107	0.047	0.073	0.229	0.109	0.170	0.169	0.309	0.421	0.112	0.281
Simulated mean	0.252	0.109	0.076	0.146	0.168	0.285	0.207	0.220	0.148	0.250	0.138	0.178
Observed std	0.104	0.232	0.092	0.142	0.229	0.155	0.205	0.161	0.337	0.421	0.088	0.277
Simulated std	0.092	0.071	0.046	0.069	0.104	0.089	0.113	0.072	0.090	0.183	0.061	0.099
R^2	0.83	0.91	0.95	0.89	0.90	0.34	0.09	0.44	0.02	0.59	0.80	0.51
p Value†	*0.0001*	0.97	0.20	0.08	0.32	*0.02*	0.67	0.36	0.30	0.23	0.20	0.30
Organic P												
Observed mean	0.021	0.010	0.007	0.013	0.081	0.017	0.035	0.045	0.047	0.128	0.019	0.064
Simulated mean	0.038	0.010	0.018	0.022	0.095	0.007	0.041	0.049	0.115	0.221	0.030	0.122
Observed std	0.027	0.013	0.011	0.015	0.090	0.020	0.044	0.050	0.057	0.179	0.018	0.083
Simulated std	0.073	0.022	0.043	0.046	0.153	0.011	0.050	0.059	0.158	0.181	0.028	0.110
R^2	0.40	0.95	0.99	0.78	0.17	0.01	0.00	0.10	0.46	0.23	0.40	0.35
p Value†	0.52	0.90	0.42	0.53	0.82	0.31	0.84	0.94	0.24	0.27	0.26	0.18
Soluble P												
Observed mean	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.030	0.050	0.001	0.027
Simulated mean	0.010	0.010	0.005	0.008	0.041	0.010	0.033	0.028	0.037	0.055	0.025	0.039
Observed std	0.000	0.001	0.000	0.000	0.001	0.000	0.001	0.001	0.046	0.076	0.001	0.041
Simulated std	0.016	0.018	0.009	0.014	0.035	0.012	0.028	0.021	0.030	0.043	0.022	0.03
R^2	0.99	0.97	0.92	0.97	0.96	0.53	0.73	0.82	0.05	0.17	0.71	0.22
p Value†	0.19	0.24	0.26	0.22	0.04	0.09	0.04	0.03	0.76	0.86	0.04	0.47

† H_0: the difference between the simulated and observed annual values was not significantly different from zero; H_0 is rejected if p value is less than the level of significance ($\alpha/2 = 0.025$). Italicized p values were less than 0.025.

sons) between simulated and observed monthly values were not significantly different from zero, except for organic N loss from SW4, mineral N loss from SW3 and SW4, and soluble P loss from SW2, SW9, and SW7 (Table 11). The losses of P were extremely low with observed values frequently below the method detection

Table 11. Observed and simulated nutrient losses based on the monthly values of 1999–2004 ($N = 72$).

Parameter	Control SW3	Control SW5	Control SW8	Conventional SW2	Conventional SW4	Conventional SW9	Intensive SW1	Intensive SW6	Intensive SW7
	kg ha^{-1}								
Organic N									
Observed mean	0.020	0.007	0.006	0.047	0.012	0.048	0.073	0.067	0.026
Simulated mean	0.020	0.007	0.011	0.070	0.003	0.040	0.071	0.131	0.018
Observed std	0.081	0.022	0.030	0.108	0.032	0.132	0.287	0.179	0.071
Simulated std	0.098	0.050	0.090	0.368	0.014	0.192	0.312	0.434	0.062
R^2	0.91	0.02	0.83	0.14	0.65	0.33	0.85	0.27	0.42
p Value†	0.948	0.993	0.515	0.570	*0.001*	0.680	0.850	0.151	0.225
Mineral N									
Observed mean	0.006	0.009	0.004	0.019	0.009	0.014	0.026	0.035	0.009
Simulated mean	0.021	0.009	0.006	0.014	0.024	0.017	0.012	0.021	0.012
Observed std	0.031	0.067	0.027	0.072	0.049	0.049	0.109	0.120	0.029
Simulated std	0.022	0.015	0.011	0.027	0.030	0.033	0.021	0.058	0.020
R^2	0.44	0.54	0.70	0.61	0.14	0.34	0.31	0.47	0.62
p Value†	*<0.001*	0.979	0.285	0.420	*0.010*	0.506	0.254	0.184	0.307
Organic P									
Observed mean	0.002	0.001	0.001	0.007	0.001	0.003	0.004	0.011	0.002
Simulated mean	0.003	0.001	0.002	0.008	0.001	0.003	0.010	0.018	0.002
Observed std	0.006	0.003	0.003	0.018	0.005	0.009	0.011	0.030	0.005
Simulated std	0.016	0.006	0.012	0.042	0.003	0.016	0.041	0.063	0.009
R^2	0.70	0.90	0.95	0.18	0.31	0.18	0.34	0.36	0.44
p Value†	0.275	0.859	0.394	0.805	0.099	0.777	0.180	0.198	0.241
Soluble P									
Observed mean	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.004	0.000
Simulated mean	0.001	0.001	0.000	0.003	0.001	0.003	0.003	0.005	0.002
Observed std	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.023	0.000
Simulated std	0.003	0.004	0.002	0.009	0.004	0.008	0.007	0.012	0.006
R^2	0.85	0.87	0.88	0.69	0.72	0.64	0.34	0.27	0.81
p Value†	0.026	0.074	0.175	*0.002*	0.050	*0.004*	0.690	0.869	*0.003*

† H_0: the difference between the simulated and observed monthly values was not significantly different from zero; H_0 is rejected if p value is less than the level of significance ($\alpha/2 = 0.025$). Italicized p values were less than 0.025.

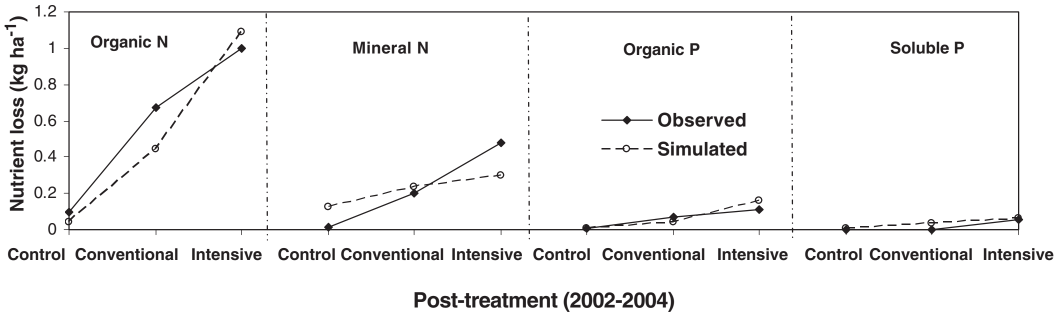

Fig. 7. Simulated and measured average annual nutrient losses (average of three watersheds).

limit of 0.01 mg L^{-1}. The very low loads observed contributed to the poor comparison. APEX predicted 0.003, 0.003, and 0.002 kg ha^{-1} of average monthly soluble P losses from SW2, SW9, and SW7, respectively. However, the correspondingly average monthly values observed were 0.

APEX tracked the pattern that N and P losses increased for clear-cut watersheds compared to the control watersheds (Fig. 7). Before treatment, there was no significant difference among nutrient losses from treatment-grouped watersheds based on ANOVA contrast analysis (SAS Institute, 1999) for both observed and simulated data (Table 7). After treatment, the organic N losses from the intensive and conventional watersheds were increased significantly compared with the losses from the control watersheds as indicated by the *p* values in Table 7. However, APEX did not detect the significant difference of mineral N losses between the intensive and control watersheds based on the *p* value at the 90% confidence level (Table 7). Although P losses were extremely low, APEX was able to predict the greater P losses from the intensive watersheds than from the control watersheds as indicated by the *p* values in Table 7.

Herbicide Losses

Observed and simulated annual herbicide losses are listed in Table 12. Standard deviations, EF, and R^2 calculations were not performed for individual watersheds because only 3 yr of data were available for each watershed for the study period. However, these statistical measures were calculated across the watersheds for a total of 18 observations (Table 13). Observed hexazinone losses from SW6 on 24 June 2003, 16 Nov. 2003, and 1 May 2004 (7.2 g ha^{-1}) were extremely high (p value < 0.0001) when compared with that from other watersheds, which lead to higher (p value < 0.0001) annual totals for these 2 yr (Table 12). Therefore, these hexazinone data were assumed to be outliers and not used when calculating the statistics in Table 13. At the annual level, the model performance for her-

Table 12. Observed and simulated herbicide losses based on the annual values of 2002–2004.

		Imazapyr			Hexazinone		
Parameter		Observed	Simulated	Difference	Observed	Simulated	Difference
		g ha^{-1}					
Intensive							
SW1	**2002**	**4.610**	**3.910**		**0.000**	**0.000**	
	2003	**0.441**	**0.106**		**0.004**	**0.059**	
	2004	**0.000**	**0.004**		**1.078**	**0.979**	
	Avg.	**1.684**	**1.340**	**−0.344**	**0.361**	**0.346**	**−0.015**
SW6	**2002**	**4.928**	**2.971**		**0.000**	**0.000**	
	2003	**1.045**	**0.160**		**3.546**	**0.151**	
	2004	**0.000**	**0.005**		**10.761**	**0.200**	
	Avg.	**1.991**	**1.045**	**−0.946**	**4.769**	**0.117**	**−4.652**
SW7	**2002**	**2.944**	**3.294**		**0.000**	**0.000**	
	2003	**0.489**	**0.126**		**0.211**	**0.091**	
	2004	**0.000**	**0.007**		**0.576**	**0.927**	
	Avg.	**1.144**	**1.142**	**−0.002**	**0.262**	**0.339**	**0.077**
Conventional							
SW2	**2002**	**0.556**	**3.998**		**0.000**	**0.000**	
	2003	**0.359**	**0.244**		**0.326**	**0.090**	
	2004	**0.000**	**0.004**		**0.000**	**0.000**	
	Avg.	**0.305**	**1.415**	**1.110**	**0.109**	**0.030**	**−0.079**
SW4	**2002**	**0.175**	**1.093**		**0.000**	**0.000**	
	2003	**0.034**	**0.112**		**0.080**	**0.083**	
	2004	**0.000**	**0.006**		**0.000**	**0.000**	
	Avg.	**0.070**	**0.404**	**0.334**	**0.027**	**0.028**	**0.001**
SW9	**2002**	**6.984**	**6.215**		**0.000**	**0.000**	
	2003	**1.407**	**0.200**		**0.771**	**0.160**	
	2004	**0.000**	**0.004**		**0.000**	**0.000**	
	Avg.	**2.797**	**2.140**	**−0.657**	**0.257**	**0.053**	**−0.204**

Table 13. Statistics for simulated and measured herbicide losses based on the annual values of 2002–2004 across watersheds.

Parameter	No. Obs.	Observed mean	Measured mean	Observed std	Measured std	EF†	R^2	p Value
	g ha^{-1}							
Imazapyr loss	18	1.332	1.248	2.101	1.924	0.73	0.74	0.75
Hexazinone loss	16	0.190	0.149	0.333	0.318	0.65	0.68	0.41

† EF, Nash-Sutcliffe efficiency.

bicide losses was satisfactory with EF of 0.73 and R^2 of 0.74 for imazapyr, and EF of 0.65 and R^2 of 0.68 for hexazinone. At the monthly level, the R^2 values were larger than 0.5 for all watersheds with the exception of hexazinone loss from SW6 (Table 14). Differences between simulated and observed monthly herbicide losses were not significantly different from zero, except for herbicide losses from SW6. Herbicide loss is sensitive to soil type and soil properties, such as organic carbon content and soil structure. In this study, only the dominant soil type, Cuthbert, and the same set of soil properties retrieved from the SSURGO database, was assumed representative of the uplands of all watersheds for the APEX simulation. This simplification might not well represent all the watersheds, which might contribute to the poor performance. Hexazinone was applied in April 2003. The first runoff-producing storm occurred in June, about 2 mo after the application. Among the six treated watersheds, four watersheds had 100% of annual hezazinone losses in June, with 94% annual loss from SW9 in June. However, there were about 35% of annual hezazinone losses that occurred in November from SW6, compared with almost no losses that month from the other five treated watersheds. Hexazinone was applied again in April 2004 in a banded application on intensive watersheds (SW1, 6, and 7). There were 96 and 100% of annual hexazinone losses that occurred in April from SW1 and SW7, respectively. Only 31% of annual hexazinone losses occurred in April from SW6.

Observed and simulated monthly herbicide losses for the treated watersheds are plotted in Fig. 8 and 9. Herbicide concentrations peaked during the first storm event after application. The losses of imazapyr that occurred in November 2002 were about 55 to 74% of the corresponding total annual losses for each watershed, due to high precipitation and thus high flow that occurred after application. It appears that APEX overpredicted imazapyr losses on small events (Fig. 8). Overprediction of flow, for example, the overprediction of 22% flow on SW2 in December 2002 might contribute to the overprediction of imazapyr loss in December. APEX also underpredicted hexazinone losses in June 2003. The underpredicted flow in June 2003 (Fig. 3) might contribute to the underprediction of hexaxinone losses.

CONCLUSIONS

The APEX model was tested for its ability to predict stream flow, sediment, organic N, mineral N, organic P, soluble P, and herbicide losses for three treatments over 6 yr (1999–2004) on nine small (2.58 to 2.74 ha) forested watersheds (loblolly pine plantations) located in southwest Cherokee County in East Texas. Watersheds received one of the three treatments: (a) undisturbed control; (b) clear-cut followed by herbicide site preparation and replanting (conventional); and (c) clear-cut followed by herbicide site preparation, subsoil, replanting, and fertilizer application (intensive).

Stream flow and sediment losses predicted by APEX on both an annual and monthly basis were acceptable for all nine watersheds. The EF values ranged from 0.68 to 0.94 and R^2 values from 0.69 to 0.97 for annual flow, with EF > 0.4 and R^2 > 0.5 for monthly flow for all watersheds. For annual sediment loss comparisons,

Table 14. Observed and simulated herbicide losses based on the monthly values of 2002–2004.

	Intensive			Conventional		
Parameter	SW1	SW6	SW7	SW2	SW4	SW9
	g ha^{-1}					
Imazapyr loss						
Observed mean	0.187	0.221	0.127	0.034	0.008	0.311
Simulated mean	0.149	0.116	0.127	0.157	0.045	0.238
Observed std	0.680	0.657	0.406	0.097	0.024	1.049
Simulated std	0.582	0.469	0.514	0.567	0.144	0.890
R^2	0.99	0.92	0.83	0.56	0.86	0.97
p Value†	0.10	0.04	0.99	0.21	0.13	0.11
Hexazinone loss						
Observed mean	0.040	0.530	0.029	0.012	0.003	0.029
Simulated mean	0.038	0.013	0.038	0.003	0.003	0.006
Observed std	0.200	1.550	0.117	0.063	0.015	0.139
Simulated std	0.187	0.041	0.176	0.012	0.010	0.018
R^2	0.99	0.18	0.90	0.54	0.51	0.65
p Value†	0.60	0.09	0.56	0.41	0.96	0.36

† H_0: the difference between the simulated and observed monthly values was not significantly different from zero; H_0 is rejected if p value is less than the level of significance ($\alpha/2 = 0.025$).

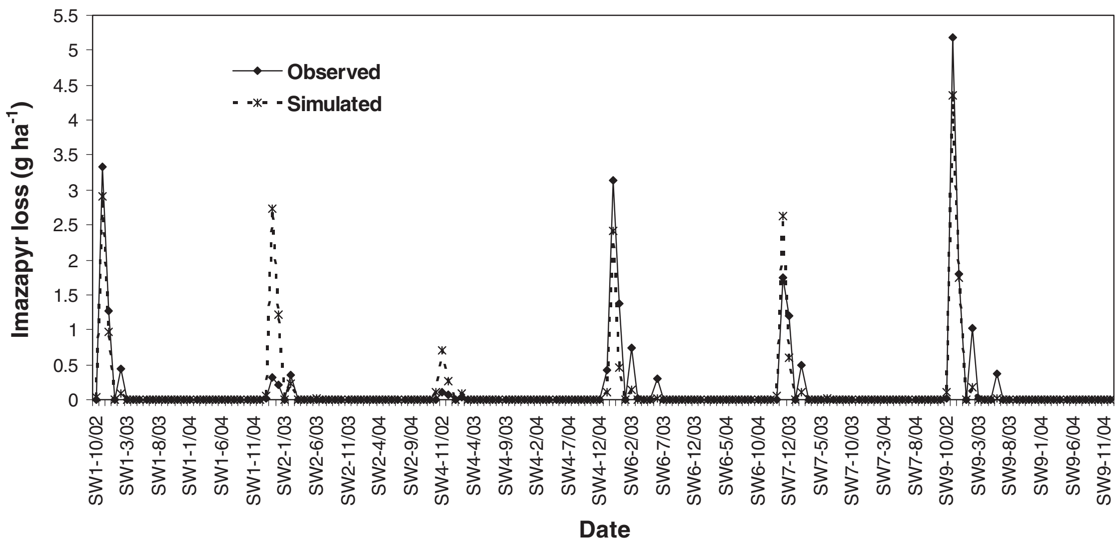

Fig. 8. Simulated and measured monthly imazapyr losses for all treated watersheds.

EF values ranged from 0.60 to 0.99 and R^2 values ranged from 0.68 to 0.99. The percent errors for all treatments were within 2% based on annual average flows of three replicates and within 5% based on annual average sediment losses of three replicates. Flow, sediment, organic N, and P losses were significantly higher on clear-cut watersheds compared with control watersheds. The losses of P were extremely low, with observed values frequently below the method detection limit of 0.01 mg L^{-1}. APEX performance for herbicide losses was reasonable with EF of 0.73 and R^2 of 0.74 for imazapyr, and EF of 0.65 and R^2 of 0.68 for hexazinone based on annual values. The R^2 values were larger than 0.5 for all watersheds based on monthly values, except for hexazinone loss from SW6.

Paired *t* tests based on annual and monthly comparisons of flow, sediment, organic N, mineral N, organic P, soluble P, and herbicide losses indicated that most of the differences (in 111 out of 122 comparisons) between simulated and observed values were not significantly different from zero. Overall, these results suggest that the uncalibrated APEX reasonably predicted flow, sediment, nutrient, and herbicide losses. The model can be a useful tool for simulating water quantity and quality responses to forest conditions and silvicultural practices with BMPs.

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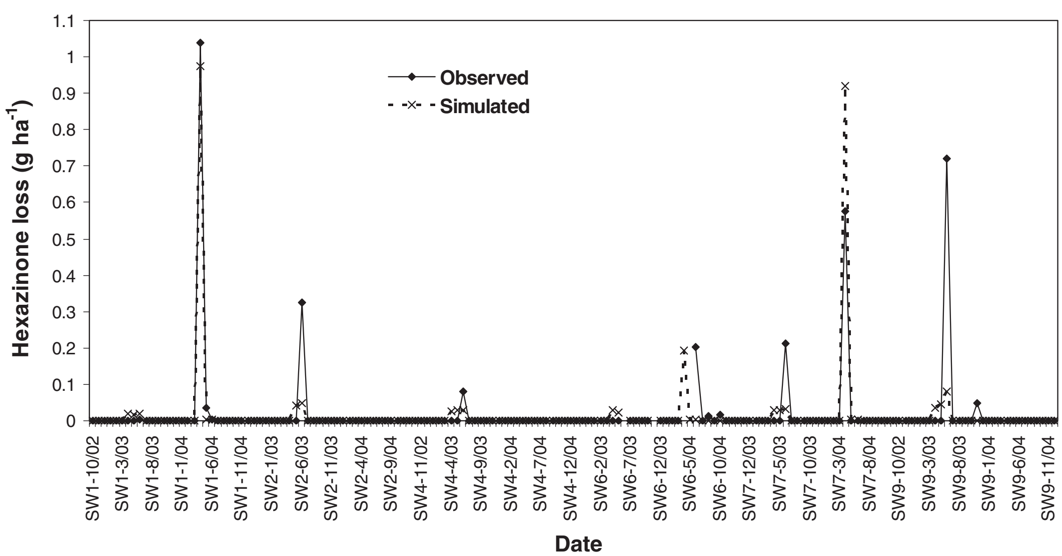

Fig. 9. Simulated and measured monthly hexazinone losses for all treated watersheds.

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